# Electron energization through spontaneous turbulent magnetic reconnection at nonrelativistic perpendicular shocks

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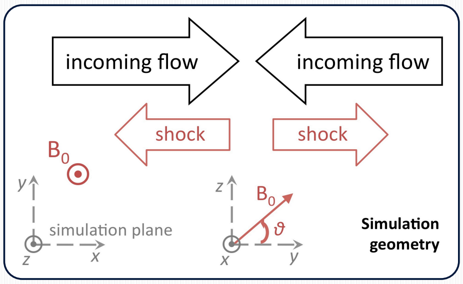
**ABSTRACT**

Results of recent kinetic two-dimensional particle-in-cell studies of high Mach-number nonrelativistic perpendicular shocks with applications to young supernova remnants are reported. These new large-scale simulations sample a representative portion of the shock surface to fully account for time-dependent effects. They are performed for different orientations of the average large-scale magnetic field with respect to the 2D simulation plane to allow an insight into the 3D physics. We discuss the nonlinear shock structure and particle energization processes with emphasis on the dynamics on electron heating and pre-acceleration needed for their injection into diffusive shock acceleration. To this end we investigate the microphysics of electron acceleration during spontaneous turbulent magnetic reconnection at the shock ramp and compare the efficiency of these processes to electron energization resulting from their interactions with electrostatic Buneman modes in the shock foot. The influence of the global shock front nonstationarity effects such as the shock rippling and self-reformation is also discussed.

## 1. INTRODUCTION

The microphysics of high Mach-number perpendicular shocks is governed by ion reflection from the shock that in the weakly magnetized plasmas leads to the formation of magnetic filaments in the shock ramp via Weibel-type filamentation instabilities [1]. Under conditions found at young SNRs electrostatic Buneman modes also appear in the shock foot and provide for the electron pre-acceleration and heating in the so-called shock-surfing acceleration (SSA) process [2].




We study electron acceleration at shocks with 2D PIC simulations in a wide parameter range, including different orientations of the large-scale perpendicular magnetic field with respect to the 2D simulation plane (angle $\vartheta$, Fig. 1).

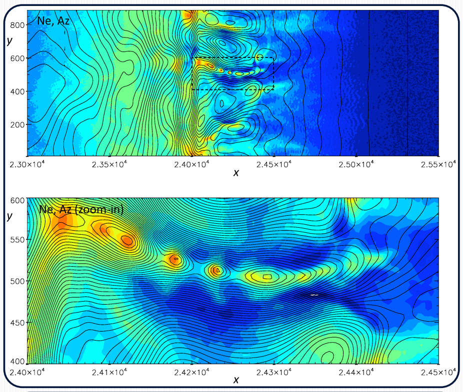



**Fig. 2: 2D distribution of the out-of-plane component of the vector potential, $A_z$ (black contours), near the shock front, overlaid on the electron density map (*top*). Blow-up of the region harboring magnetic islands, indicating the spontaneous magnetic reconnection (*bottom*).**

## 3. RESULTS

Depending on the magnetic field geometry, different electron acceleration processes occur:

- For $\vartheta$=90° particles undergoing SSA in the shock foot are further adiabatically energized in the shock ramp through grad-B drift.
- For $\vartheta$=0° and $\vartheta$=45°, merging of magnetic filaments can lead to spontaneous magnetic reconnection in the shock ramp (Fig. 2), that provides another channel for electron energization at the shock [3]. Particles can be non-adiabatically accelerated by colliding with moving magnetic structures in the shock transition (Fig. 4). They can also gain energies by direct interaction with the reconnection structures, e.g., with the X-points (Fig. 5), within magnetic islands, and by bouncing between colliding islands.

The acceleration efficiency depends on the magnetic field orientation and vary from 1% for $\vartheta$=0° and 2% for $\vartheta$=90°. The efficiency changes with the phase of the cyclic shock self-reformation and inflowing plasma temperature.

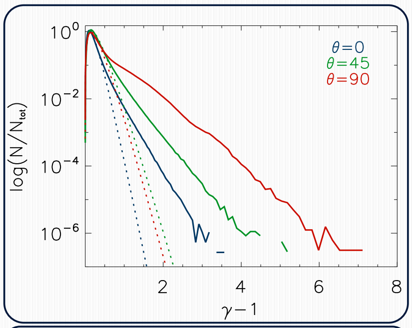



**Fig. 3: Accelerated electron spectra downstream of the shock for different orientations of the large-scale perpendicular magnetic field to the 2D simulation plane: in-plane (0°); 45°, and out of plane (90°). Fits of the Maxwellian distribution to each spectra are shown with dotted lines.**

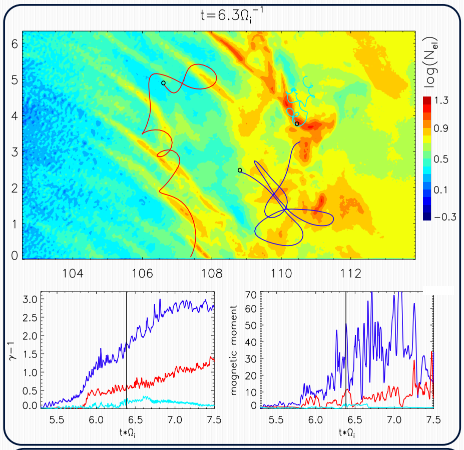



**Fig. 4: Typical particle trajectories overlaid on the electron density structures at the shock. Open circles mark particle positions at $t\Omega_i$=6.3, and their trajectories are followed back for $t\Omega_i$=0.25 (*top*). Full energization and magnetic moment histories for the sampled particles (*bottom*). Far upstream magnetic field is in 2D simulation plane (0°).**

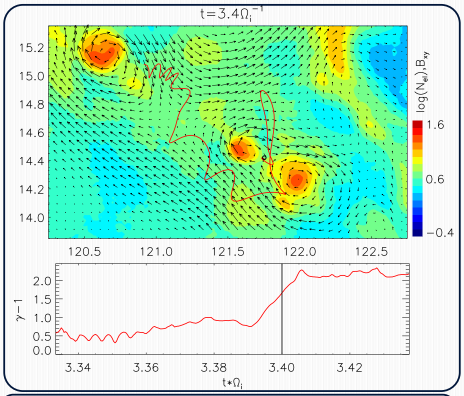



**Fig. 5: Example trajectory and energization history of a particle interacting with the reconnection region formed in the shock ramp. The most significant energy is acquired through the interaction with the dissipation electric field at the X-point (see Fig. 4).**

**REFERENCES**

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